Large-Eddy Simulations of the Tropical Boundary Layer and Upper Ocean Coupling in the Arabian Sea

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LONG-TERM GOAL

Improve operational numerical weather prediction (NWP) models to more accurately simulate the interaction of tropical deep convection and atmospheric and oceanic boundary layers.

OBJECTIVES

The main scientific objective of this study is to better understand the role of boundary layer coupling in determining how surface ocean properties are controlled by atmospheric processes. Simulations of both the atmospheric and ocean boundary layers will be used in conjunction with a range of atmospheric observing platforms to identify how moisture and heat transfer between the ocean and atmosphere control the overall energy balance of the two systems. Specific objectives are to:

- Examine how atmospheric convection and convectively produced precipitation control the boundary layer structure and surface air-sea interaction
- Evaluate the ability of commonly used boundary layer parameterizations to accurately represent the tropical boundary layer
- Develop improved surface flux parameterizations that include the effects of cold pool circulations produced by convective precipitation
- Assess the importance of heat storage in the ocean mixed layer as an energy source for moistening the atmospheric boundary layer preceding the Indian Monsoon

APPROACH

The proposed objectives will be met through a combination of LES experiments and mesoscale simulations using the Navy Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS). LES cases will focus on specific boundary layer processes associated with precipitating clouds, whereas the COAMPS model will be employed to examine how these processes are represented by typical mesoscale models.

Our approach is based on using high-resolution data taken from boundary layer profiling instruments in combination with three-dimensional LES. Profiling data provide a nearly continuous picture of the velocity, temperature, and humidity for a single point in space extending upward through the boundary layer. Much can be gained through analysis of these data, however, larger scale processes, such as strong divergence and convergence regions generated from cloud systems, can only be partially understood using a single column of information.

One particular aspect of the tropical boundary layer that we seek to better understand is the role of precipitating cloud systems on the boundary layer structure and surface heat exchange. We think of the classic boundary layer structure as being controlled by mixing generated by either wind-forced turbulence or dry convection produced by surface sensible heat flux. These two sources of turbulence are critical for scaling arguments applied in surface flux parameterizations based on Monin-Obukhov similarity theory, and mixed layer models that scale the boundary layer depth to the surface flux (e.g. K-profile parameterization).

Over the tropical ocean, surface fluxes are dominated by evaporation; sensible heat flux is, for the most part, only a minor component of the overall surface flux balance. This is in contrast to a typical land-based boundary layer where sensible heat flux controls the boundary layer structure, especially during the daytime. Yet we know that the tropical boundary layer is often turbulent, even in low wind conditions, with significant vertical transport of moisture and momentum, suggesting that processes associated with the latent heat flux must be integral to the boundary layer energetics. A gap in our knowledge centers on the eddy heating term, which represents the vertical transport of heat from the free troposphere into the boundary layer and is dependent on entrainment fluxes. *Understanding this flux is a key objective of the proposed effort because it ultimately controls the air temperature near the sea surface and is a key component in setting the surface fluxes.*

We are also interested in understanding the role of mesoscale sea surface temperature (SST) variability on the formation and evolution of atmospheric convection. On small scales, convection has minimal impact on SST and only affects surface fluxes through wind speed variations. For larger scales (greater than ~500 km) SST variations are known to affect convective development (Li and Carbone 2012). It is unknown if there is a feedback between convection and larger-scale SST variability, which is one area we plan to investigate in this study.

Specific LES experiments will be based on the profiler observations taken by H. Fernando as well as routinely available radiosonde data. Cases will also be conducted to examine a range of wind forcing so that changes in the surface fluxes can be examined. On the ocean side of the LES model, we plan to evaluate how fresh water flux from rainfall accumulates to produce a barrier layer that develops during the transition periods between onshore and offshore monsoon winds. Heat buildup in the ocean mixed layer during these periods provides a source of latent heat energy that is released during the monsoon, promoting large precipitation events over India.

Simulations conducted with COAMPS will consider conditions identical to the proposed LES cases, but with much coarser model resolution so that key mixing processes, such as turbulent eddy transport and entrainment, will be parameterized. Results from these experiments will be compared with the LES and profiler measurements and used to identify shortcomings in the mesoscale model. In particular, we would like to develop new methods for including the effects of small-scale convection and precipitation on the tropical boundary layer. Current parameterizations, such as the Mellor-Yamada based mixing schemes, generate turbulence based on background shear and stability

parameters. For grid spacing above ~10 km, convection is typically parameterized so that boundary layer mixing does not necessarily include the effects of precipitation such as surface cold air outflow regions. One goal of this research is to develop methods for including these entrainment fluxes by coupling the convective parameterizations with turbulence closure schemes by enhancing mixing rates below the cloud base when convection is active in the model.

WORK COMPLETED

Funding for this project was not approved until June 2015, limiting the extent of work presented in this report. Research has mostly focused on setting up experiments to test the hypothesis that mesoscale variability in SST affects the formation of convective activity that then drives fluxes in the upper ocean. To date, two simulations have been completed for different wind directions over an idealized SST patch. Results from these two cases are presented below

RESULTS

Our work using the coupled atmosphere ocean cloud model during the last year has focused on how wind speed and sea-surface variability affects convective development. Simulations in Skyllingstad and de Szoeke (2015) considered relatively light surface wind forcing (~3-4 m s-1), where moisture flux was dominated by the large scale circulation. Here we examined a case with background winds of 18 m s^{-1}, which generated surface wind speeds around 8-9 m s^{-1} and much larger surface air-sea fluxes. Increased winds generate a more consistent vertical temperature structure that is nearly identical with the atmospheric conditions observed during the DYNAMO experiment. These simulations suggest that the stability of the equatorial atmospheric structure is consistent with the overall latent heat flux forced by convergent trade wind circulations.

We also examined the effect of SST variability on scales of ~100 km by conducting a set of experiments with a band of warmer water across the center 1/3 of the model domain. Our goal in these experiments is to determine how mesoscale variations in SST affect convective development as observed in satellite data (Li and Carbone 2012). Initial simulations using an 18 m s^{-1} northward background wind field and a 1.5 ^{o}C temperature difference for a latitude of 5 ^{o}N show increased convection over the warm patch that gradually moves to the right of the wind direction over a 4 day run period. An example of the cloud systems after 8 days is presented in Figure 1.

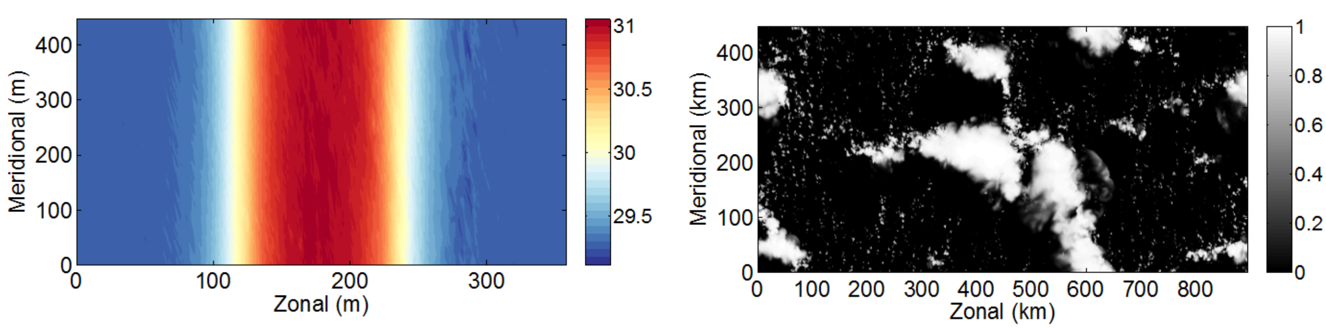

Figure 1. Sea surface temperature and Simulated cloud albedo on day 4.

Winds in this case are aligned with the SST front, which increases the time period where air parcels are adjacent to warmer water, concentrating higher fluxes over the warm patch region. Consequently, averaging the albedo over the duration of the simulation in the meridional direction shows a consistent increase in cloudiness associated with the warm water (Figure 2).

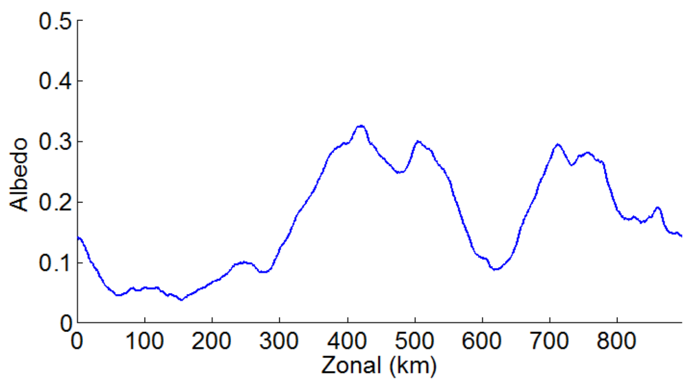

Figure 2. Albedo averaged in the meridional direction over days 2-4.

Experiments with winds at a 45 degree diagonal to the SST gradient do not show a similar behavior for 18 m s^{-1}, suggesting that for stronger winds, SST variability on scales of ~100 km does not exert a strong control on cloud structure. Future work will examine cases with weaker winds and larger regions of SST variability.

REFERENCES

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